Impact of Operating Context on the Use of Structure in Air Traffic Controller Cognitive Processes

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Abstract: This paper investigates the influence of structure on air traffic controllers' cognitive processes in the TRACON, En Route, and Oceanic environments. Radar data and voice command analyses were conducted to support hypotheses generated through observations and interviews conducted at the various facilities. Three general types of structure-based abstractions (standard flows, groupings, and critical points) have been identified as being used in each context, though the details of their application varied in accordance with the constraints of the particular operational environment. Projection emerged as a key cognitive process aided by the structure-based abstractions, and there appears to be a significant difference between how time-based versus spatial-based projection is performed by controllers. It is recommended that consideration be given to the value provided by the structure-based abstractions to the controller as well as to maintain consistency between the type (time or spatial) of information support provided to the controller.

1 Introduction

New air traffic control technologies and procedures are changing the operating conditions of the air traffic control system. In order to understand the implications of these changes on the safety of the system, a deeper understanding of the cognitive processes of air traffic controllers is needed. Previous research has identified that structure constrains the system dynamics thereby simplifying the traffic situation [1,2,3]. This in turn minimizes the cognitive load of the controllers.

While structure appears to have general benefits, how it influences cognition will depend on the specifics of the operational environment. Studies have shown that context not only determines the range of potential actions, but also influences the cognitive processes used to make the choice [4,5]. There are a variety of operational environments in Air Traffic Control. In the oceanic environment controllers must deal with poor surveillance and convoluted communication procedures. In contrast, the domestic radar environment has 4.8-second update rate radar and direct voice communication to the pilots. This paper examines the influence of structure on controllers' cognitive processes across the wide range of air traffic control operational environments.

2 Methodology

A series of site visits to ATC facilities in the United States, Canada, and Iceland have been conducted. TRACON sites observed include: Boston, New York and Manchester; En Route Centers observed include Boston, Cleveland, New York, and Montreal. Oceanic operations observed include
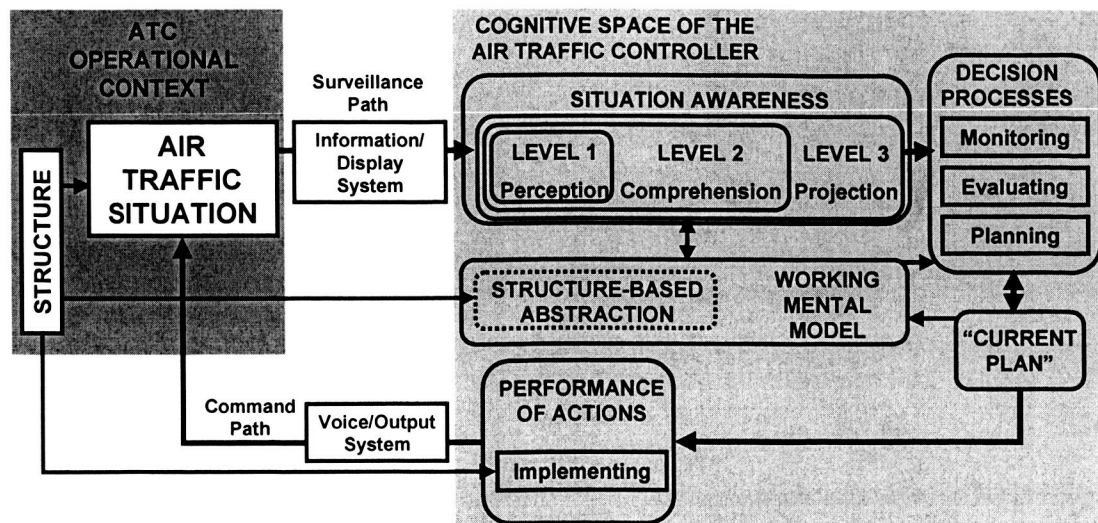
Figure 1: Generalized model of a subset of the cognitive space of an air traffic controller (adapted from Endsley[6])

Reykjavik Area Control Center and New York Center.

The site visits consisted of focused interviews with controllers and training personnel as well as observations of live operations. To gain additional insight into the use of structural factors identified during the site visits, current traffic patterns were analyzed using data derived from the Enhanced Traffic Management System (ETMS) data-stream. Content analyses of controller-pilot voice communications within Boston TRACON were also performed to support hypotheses of controller-imposed structure.

3 Generalized ATC Process Model and the Influence of Structure

A generalized model capturing the key processes of an individual air traffic controller was assembled from field observations and from a broad review of the relevant literature. The resulting model is depicted in Figure 1. The model is consistent with and partly based upon previous research by Endsley [6] and Pawlak [7]. This conceptual model also describes some of the observed and hypothesized interactions between structure and the cognitive processes of an air traffic controller.

The primary processes observed include:
- Perceiving
- Comprehending
- Projecting
- Monitoring
- Evaluating
- Planning
- Implementing

3.1 Cognitive elements
In this model, information is fed into the controller through **Perception**, primarily through the auditory and visual modalities. This information is then **Comprehended** in relation to the goal-relevant tasks of the controller. A **Projection** of the immediate future state of the system is then created using information from the environment that feeds experience-based mental models of the system entities. Gathering and using this information to project into the future was termed the Maintenance of Situation Awareness by Endsley [6].

The projection created in the Situation Awareness portion is then **Monitored** against the controller's "Current Plan". If the projection is not entirely consistent with the "Current Plan", the future state of the system is then **Evaluated** with respect to the controller's threshold of acceptability. If the projected state of the system is in conflict with the set constraints, **Planning** is then used to generate an action that not only will return the projected state adequately within the boundaries, but that will also minimize the monitoring requirements imposed on the controller.

In the model, the **"Current Plan"** is generated by the controller's planning process and is greatly influenced by past experience. The "Current Plan" represents the controller's internal representation of a time-dependent schedule of events and commands to

be implemented as well as the resulting aircraft trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner.

The "Current Plan" feeds the **Action Implementation** process, determining the time at which the controller commands the pilots, either through voice or through information tools (e.g., datalink). Through a surveillance path, the impact of those commands on the **Air Traffic Situation** is fed back to the controller's Situation Awareness process.

3.2 Structure

Structure is embedded within the ATC operational context. Various forms of structure have been identified as having a significant influence on the controllers' cognitive processes and perceived cognitive complexity of an Air Traffic Control situation [1,2,3]. Structure is defined as a set of constraints (either physical or human-imposed) that limits the evolution of the dynamics of the system. Based upon observations and interviews, structure appears to influence the cognitive processes by providing a basis for abstractions that simplify a controller's mental model. Several key structure-based abstractions have been identified in prior studies and are illustrated schematically in Figure 2.

Standard Flows

The standard flow abstraction emerges as a means of classifying aircraft into standard and non-standard classes on the basis of their membership in established flow patterns in a sector. An aircraft identified as a member of a standard flow carries with it an associated set of higher-level attributes such as expected future routing, ingress and egress points from the airspace, and locations of probable encounters. These attributes form a generalized expectation of an aircraft's trajectory through the airspace.

Examples of the standard flow have been identified in both European and North American ATM systems. Figure 3 and Figure 4 show 24 hours of traffic destined to Charles de Gaulle airport in Paris and O'Hare airport in Chicago respectively. The figures demonstrate the standard flows that emerge from the consolidation of aircraft onto standard arrival routes to an airport. The presence of these standard flows provides the basis for abstractions that simplify the projection task for controllers.
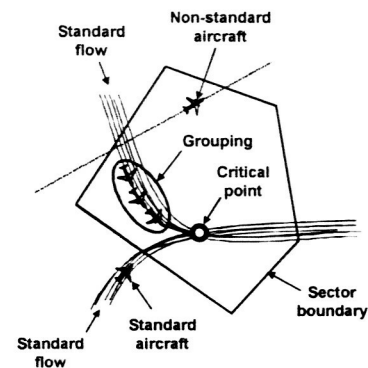

Figure 2: Illustration of structure-based abstractions: Standard flows, Groupings, and Critical points.
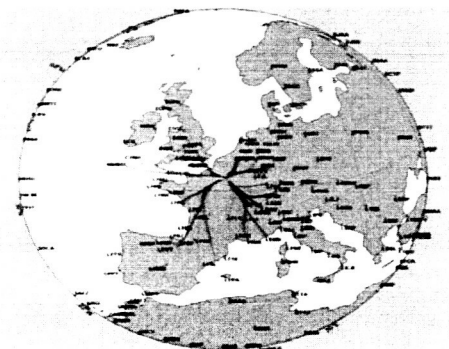

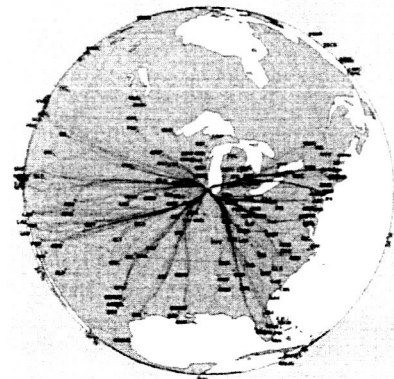Figure 3: Traffic flows to Charles de Gaulle in Paris (LFPG)

Figure 4: Traffic flows to O'Hare Airport in Chicago (ORD)

Groupings

A common property shared by a set of aircraft can form the basis of a grouping abstraction. Often the relevant property is based on an aircraft's relationship to the structure of the underlying airspace.

The grouping abstraction can also operate on the basis of the simple proximity of aircraft, as shown in

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Figure 2. In this case, the use of a grouping abstraction can act to simplify the output from a controller, i.e. the execution of the results from the decision process. This may occur when several aircraft are given identical clearances or multiple aircraft divert around convective weather.

Critical points
Critical points in the airspace were also identified as an example of a structure-based abstraction. The underlying structure, in the form of crossing and merge points of flows, will tend to concentrate the occurrences of encounters at common locations, also illustrated in Figure 2. Focusing on the intersection points of aircraft flows reduces the need for controllers to evaluate the potential for conflict over all possible pairs of aircraft within those flows [1]. The interaction between two aircraft approaching a merge point reduces a 4 dimensional conflict to a one- or two-dimensional phasing problem. The same encounter geometry in the absence of a known critical point abstraction may require consideration of multiple dimensions, making the projection task more difficult.

4 Impact of Structure in varying ATC Operational Environments

The purpose of this paper is to investigate similarities and differences in how structure-based abstractions are used across different ATC operational environments. In each of the following sections, the particular operational environment is discussed in reference to the general ATC process model in Figure 1 and contextual examples of the existence and use of the different types of structure-based abstractions discussed above are outlined and supported through observational and air traffic data.

4.1 TRACON Environment

The Terminal Radar Control (TRACON) environment typically extends to 18,000 ft and approximately 40 miles from high-density airports. In this environment, the command/surveillance loop in Figure 1 provides timely feedback to the controller with 4.8 sec radar update rate and VHF voice aircraft. In this highly time-critical environment, aircraft are in the closest proximity to one another than at any other point during their flight. The transitional nature of this ATC environment also contributes to making the TRACON control task a particularly challenging one.

The final approach controller is required to perform precise vectoring commands to ensure the ILS is captured by each IFR. Constraints present in the

TRACON environment include traffic restrictions that must be met either in terms of miles or minutes in trail, weather, noise abatement procedures, airspace, and wake turbulence restrictions on final and departure.

Standard Flows
The default route in the TRACON is the standard arrival route based on the TRACON's Standard Operating Procedures (SOPs) on final approach. The SOPs' standard departure procedures supplement the Standard Instrument Departures (SIDs) used by the pilots. Constraining the locations of the aircraft both laterally and vertically influences the situation awareness block in Figure 1 by reducing the perceptual load through the expectation that most aircraft will be along the standard routings, allowing more efficient information sampling. In addition, the comprehension and projection tasks are aided in that the aircraft locations on the standard routings imply the subsequent states along the standard route.

In the planning stage of cognitive processing, the standard arrival and departure routes provide a template of the desired route, which can be used for command (i.e., vector) planning as well as traffic monitoring. The standard routes are also useful because constraints such as noise abatement procedures, airspace, and proceduralized handoff requirements established by Letters of Agreement (LOAs) between facilities must be adhered to, limiting potential novel routings. Arranging a novel route can multiply cognitive load on the controller, therefore if the nominal standard routings are not appropriate, experience-tested alternate routes are often used, which act as informal alternate routes.

In Figure 3, an example of Standard Operating Procedures for runway configuration landing 4R/4L into Boston is illustrated. The expected ingress points for jet arrivals are BRONC, SCUPP, and PVD. Propeller aircraft are fed to the TRACON from BRONC, LWM VOR, SCUPP, FREDO, and WOONS. The expected egress route from the TRACON to the Tower is the Final Approach Fix, where the aircraft has, in normal instrument circumstances, captured the ILS. To maintain flexibility within the facility, however, TRACON controllers may direct traffic through vectoring that often departs from the SOP's standard arrival/departure routes.

The SOP does, however, establish a standard flow for the TRACON controllers. Radar trajectories of arrivals into and departures from the Boston T
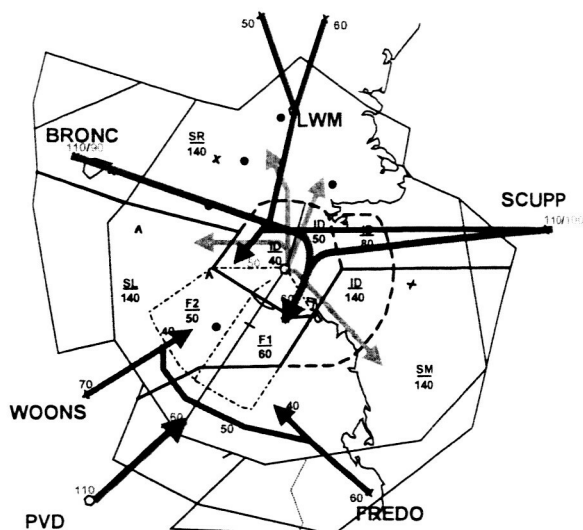
Figure 3: Standard arrival routes into Boston TRACON for a Runway 4R/4L arrival.

RACON for December 16, 2002 are shown in Figure 4. Clearly, even though controllers can deviate from the standard arrival route, the standard flow emerges from this structured procedure.

Groupings

It has been observed in prior research that controllers use groupings to cognitively simplify mental calculations about the traffic situation. In the observations conducted at the TRACON, controllers appear to group aircraft by altitude, airspeed, and by destination (for departures).

Because procedures require 1000 ft separation in the TRACON, altitude commands are normally discretized into even thousands. Within these discrete altitudes, controllers can use altitude to provide a robust means of separation assurance. If two aircraft appear to be merging laterally (due to procedural requirements such as at a merging point), separating them in altitude frees controller monitoring resources for other tasks, as can be seen in Figure 5, where two jet arrival flows merging in the Boston TRACON are depicted. Distinct altitude shelves can be discriminated between the two flows. Each flow is kept separate by 1000 ft until the flows are merged laterally, then the flows are merged vertically.

Controllers also group aircraft by airspeed. Voice command analyses performed in the Boston TRACON final approach sector indicate that controllers not only structure the airspeeds of aircraft within their sector, but also structure the airspeeds to be similar across the merging paths. Figure 6 depicts
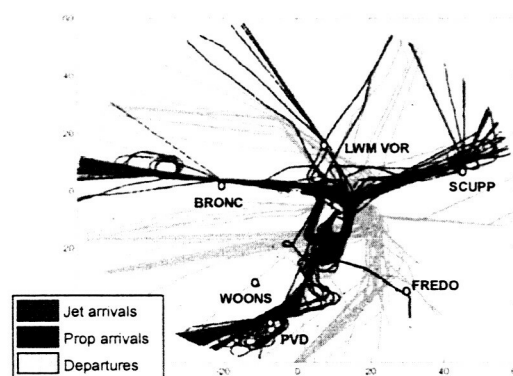

Figure 4: Radar trajectories of departures and arrivals in Boston TRACON on Dec. 16, 2002.
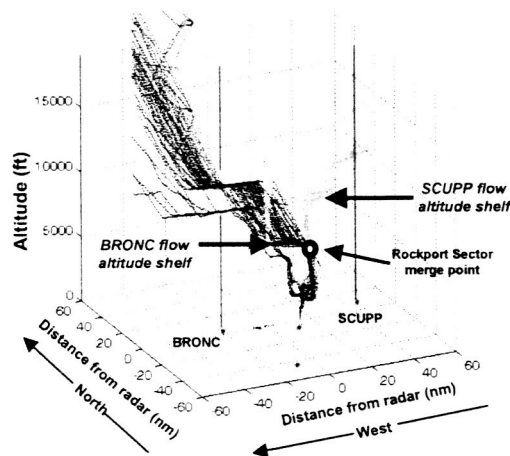

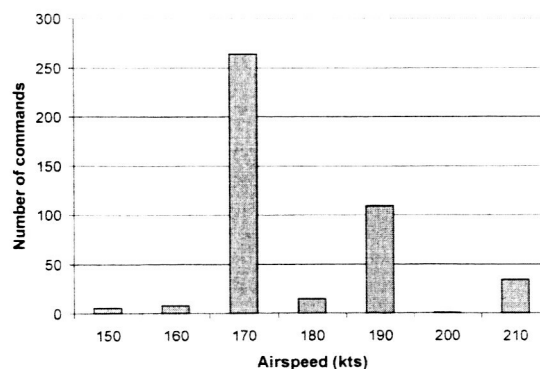Figure 5: Altitude transitions of merging jet arrivals from BRONC & SCUPP on December 16-17, 2002.

Figure 6: Frequency distribution of airspeed commands for all aircraft through the Final Approach sector of the Boston TRACON on September 25, December 16 & 17, 2002.

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the voice command distribution of the final approach sector for a landing runway 4R/4L configuration. 170 kts is the most frequent speed command used in the final approach sector.

It is hypothesized that controllers impose airspeed structure to simplify the cognitive projection task. By reducing the speed variation, the controller is reducing the complexity of the task from a 4-dimensional projection to a projection task in which time and distance are correlated.

Simple heuristics also aid the controller in the projection, monitoring, and evaluation tasks. In the TRACON, separation requirements are in terms of miles, a spatial constraint. Controllers use a spatial display to monitor the current and projected aircraft separations. Only during a Minutes-in-trail restriction are the controllers required to separate aircraft through time rather than space. Therefore the TRACON controllers use a heuristic to transfer Minutes-in-trail requirements to Miles-in-trail, so that separation can be easily monitored on the spatial display.

Critical Points
Critical points emerged during the analysis of the traffic patterns within the Boston TRACON. An example of critical points for Boston jet arrivals is illustrated in a radar trajectory graphic in Figure 7 using December 16, 2002 data for the landing 4R/4L runway configuration. In Figure 7, the flows from the west and east are normally merged at the top critical point, located in the Rockport sector in the TRACON. In Figure 7, the second critical point merges the east/west flow with the flow from the south for arrival spacing. The Final Approach sector performs this merge. If traffic flow is light or if there

Figure 7: Illustration of critical points present in the jet arrival flow for Boston TRACON in December 2002.

are few arrivals from the south, the Final approach may accept handoffs from Rockport on the left downwind, as is evident in the picture.

Handoff points both between facilities and between sectors also emerge as critical points. These handoff points become particularly important and constraining as restrictions (e.g., Miles-in-trail) are imposed on the controller. In restriction cases, the controllers are not only projecting to evaluate separation assurance at the merge points within their sectors, but they are also projecting to ensure that aircraft leaving their sectors will meet the minimum traffic flow restrictions set by the downstream sector or facility.

These critical points appear to be useful as complexity-reduction mechanisms to the controller's cognitive projection task. By having a single critical point to which aircraft must merge, the projection task becomes a phasing problem. Reducing the number of critical points present in a sector, similar to the separation of the merge points of the arrival flows between Rockport and Final, also simplifies the controller's task.

4.2 En Route Center Environment

Center operations represent a distinct operational environment from both terminal airspace and oceanic airspace. Similar to the TRACON environment, the command path in Figure 1 consists of controller commands communicated through VHF communications. Radar displays and flight strips are the primary information display systems that form the surveillance path. However, the 12 second update rate of most en route radars is significantly slower than those used in terminal areas. The feedback path in Figure 1 is consequently longer, creating additional emphasis on accurate projections of aircraft trajectories.

Additional constraints within the Center environment exist that impact the cognitive processes in Figure 1. For example, traffic management restrictions may require controllers to hold aircraft, re-route aircraft, or vector aircraft to achieve necessary spacing or metering requirements. Los Angeles Center is testing, for example, time-based metering requirements that may transform the projecting, planning and evaluating tasks from a spatial to a temporal task [8]. Also, the presence of high altitude holding or Special Use Airspace can restrict the available airspace, limiting the solutions that can be considered in the planning process. For example,
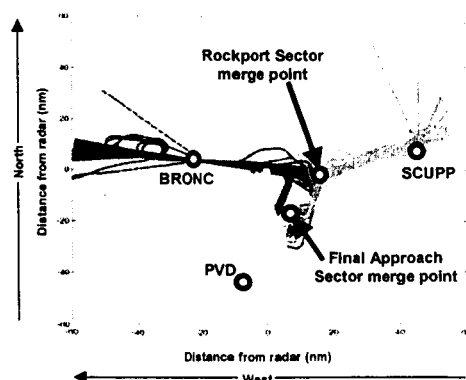
Figure 8: Special Use Airspace constrains aircraft trajectories into San Francisco (SFO).

Figure 8 shows that the trajectories of aircraft destined for San Francisco are constrained by Special Use Airspace. The presence of convective weather, turbulent conditions or strong winds limiting the acceptability of certain altitude levels can further reduce available airspace.

There exist a variety of types of operating environments within a Center. En Route sectors are typically high or "super-high" altitude sectors where most aircraft remain at a constant altitude as they traverse the sector. Figure 9 shows that almost 60% of the aircraft traversing the Utica sector (an En Route sector in Boston Center) did not change altitude.

Another type of operating environment in a Center is the transition sector, which serves as the interface between En Route sectors and the terminal airspace. These sectors control aircraft as they ascend to or descend from cruising flight levels. Figure 9 shows
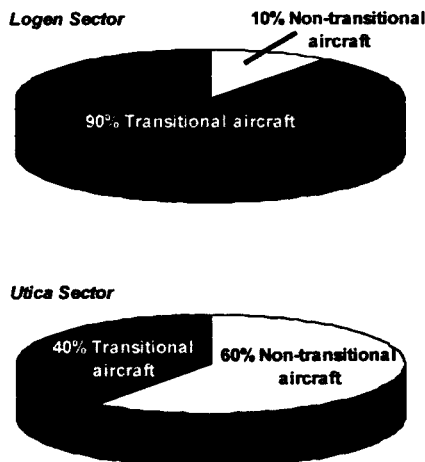
Figure 9: Transition sectors such as Logen show a greater proportion of aircraft changing altitude (red) than maintaining a constant altitude (white), as compared to en route sectors such as Utica.

that almost 90% of the aircraft through the Logen sector (a transition sector in Atlanta Center) exited the sector at a different altitude than they entered it.

Transition sectors share many of the same operational conditions as En Route sectors, such as radar update rates and limitations on available airspace. However, transition sectors often perform tasks similar to those performed in the terminal airspace with the majority of aircraft in vertical transition and a greater use of vectoring. The following sections consider the previously identified structure based abstractions for both En Route and transition sectors.

En-route Sectors

Standard Flows

Aircraft have traditionally followed air routes defined by navigational fixes that form part of a contracted clearance. With the availability of area navigation systems (GPS, INS), direct routings or routings defined by flow considerations are becoming more prevalent. Published procedures, such as ATC preferred routes, and constraints associated with procedural requirements at sector boundaries tend to consolidate the range of trajectories through an En Route sector into standard flows.

For example, Figure 10 shows the aircraft trajectories through an En Route sector, the Utica sector in Boston Center. The trajectories of aircraft that appeared to be on standard flows were identified and are highlighted by dark lines in Figure 10.

Figure 10: Image of 24 hours of traffic through Utica Sector (En Route sector).

Within the En Route environment, an aircraft is responsible for its progression along its cleared route. Consequently, aircraft tracks can and will change without any direct intervention (e.g. vectors or amended clearances) by the controller. By giving clearances that constrain aircraft tracks to the standard flows through the sector, the controller's projection task is simplified, since anticipating such behavior can be based on the knowledge of the standard routing along which the aircraft is proceeding.

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Critical Points

In the En Route environment, critical points emerge at intersection and merge points between flows. An example of an intersection point is identifiable on the left side of Figure 10. Further analysis of the trajectories showed that over 45% of all aircraft through this sector passed within a twenty-five square mile area around that critical point.

Critical points often emerge as a consequence of the merging of standard flows into high density flows into key airports. For example, Figure 11 highlights critical points defined by the merging of flows destined to Chicago from the south-east. Observations suggest that there is a maximum of a single critical point per flow sector.

Figure 11: Standard Flows of Aircraft destined for O'Hare airport in Chicago.

Merging operations which occur at a standardized location provide a basis for the critical point abstraction. The critical point abstraction can reduce a multi-dimensional interaction problem to a one-dimensional problem in which the key control parameter is "time-of-arrival" at the merge point.

Groupings

In contrast to the terminal environment and transition sectors, aircraft traversing En Route sectors typically experience fewer transitions between altitude levels. Figure 9 above suggests that most aircraft in the En Route environment are constrained to level flight at a discrete altitude level. The use of discrete altitude levels segregates the traffic into non-interacting subsets. Figure 12 shows the relative density at each altitude over a 24 hour period. Distinct bands are observable at FL 280, FL 310, FL 350, and FL 390, consistent with the expected assignment of flight levels with direction of flight.

Aircraft that are separated in altitude can be grouped into non-interacting sets. This reduces the number of

aircraft interactions that must be considered, thus simplifying the evaluating and planning tasks. It is interesting to note that many studies of complexity report that aircraft in altitude transition add significantly to the complexity of a situation (e.g. [11, 12]). This is consistent with a breakdown of the grouping abstraction. Aircraft in altitude transition cannot be grouped into non-interacting subsets based on the discrete flight levels, increasing the complexity of projecting and evaluating aircraft trajectories.
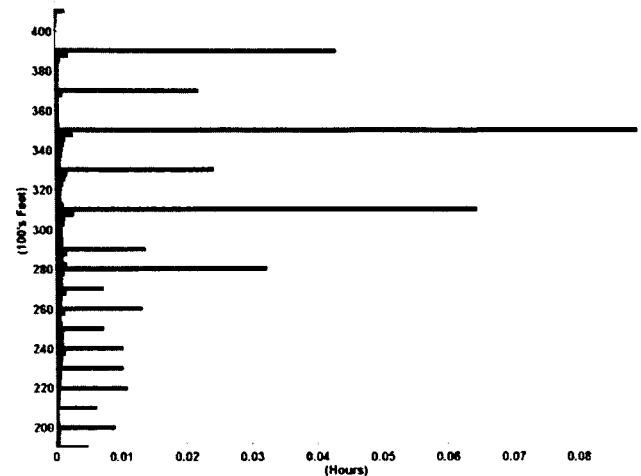

Figure 12: Relative density at each flight level for 24 hours of traffic through Utica Sector.

Transition Sectors

Standard Flows

Transition sectors control aircraft as they ascend to the En Route sectors and descend from cruise altitudes to the terminal airspace. Published procedures such as Standard Terminal Arrival Routes (STARs) and Standard Instrument Departures (SIDs) create standardized aircraft trajectories through transition sectors. An example of a STAR for aircraft arriving into Atlanta airport from the North-East is shown in Figure 13.

One of the transition sectors responsible for aircraft following this STAR is the Logen Sector in Atlanta Center. Figure 14 shows the tracks through the sector over a 24 hour period as well as key fixes from the STAR. These fixes are examples of underlying structural elements. Figure 14 demonstrates how the standard flows correspond to these underlying structural elements. During the data sample period, 61% of all aircraft through the sector were destined for Atlanta-Hartsfield airport. The standardization of the trajectories of those 251 aircraft destined for

Figure 13: MACEY TWO Standard Terminal Arrival Route (STAR) (Courtesy www.atcmonitor.com).
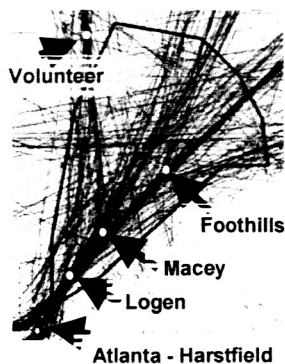
Figure 14: 24 hours of traffic through Logen sector (Oct. 18, 2001).

Atlanta, reduces the number of possible aircraft trajectories that a controller working the Logen sector must consider, simplifying the planning, monitoring, and evaluating tasks considerably.

By consolidating aircraft into standard flows, the order, or number of dimensions that are relevant to the control problem, is reduced. This effect is illustrated in Figure 14B which shows the aggregate density of the relative positions of aircraft passing through the Logen sector. Figure 14B illustrates the predominantly in-trail spacing of traffic through the Logen Sector. Analysis of communication data showed the use of common speed assignments to aircraft on similar lateral tracks. The in-trail nature of the aircraft distribution coupled with the common speed restrictions allows controllers to simplify the projection task by reducing the relative movement
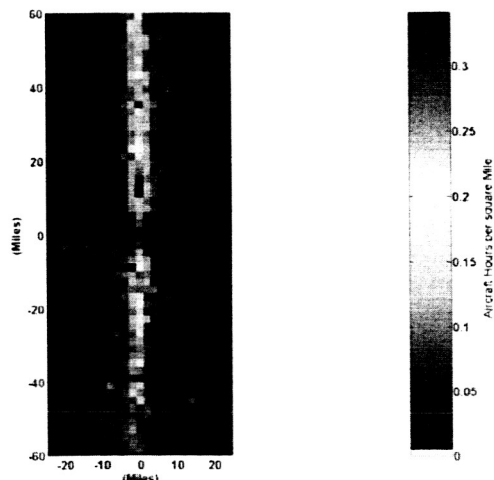

Figure 14B: Relative aircraft density for Logen Sector (Transition sector).

of aircraft to a single dimension along the lateral track.

Critical Points

Within transition sectors, critical points, such as merge points, are created by the underlying structure (e.g. STARs). The use of this underlying structure to support the critical point abstraction has been investigated through an examination of controller command outputs for the Logen sector. Controller-pilot communications for the sector were collected and analyzed for content. The results shown in Figure 15 indicate that three basic command types accounted for 61% of all issued commands over the observed period. A high percentage of the issued commands were consistent with the controllers executing the codified procedure of the STAR shown in Figure 13. For example 89% of the altitude crossing restrictions was issued for the Logen fix. The Logen fix is the likely basis for a critical point abstraction used by a controller working the Logen sector.
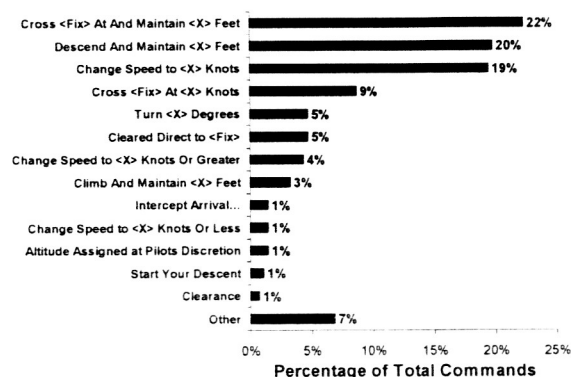
Figure 15: Relative occurrences of commands.

Grouping

The altitude behavior of aircraft in transition sectors is significantly different from that of aircraft in En Route sectors and this has a direct impact on the availability of certain grouping abstractions. As was shown in Figure 9, similar to the terminal environment, transition sectors have a much higher rate of altitude transitions than En Route sectors. Instead, aircraft are grouped into "transitioning" and "non-transitioning" groups.

There are also other structural basis for a grouping abstraction such as, grouping abstractions based on the destinations of aircraft.

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4.4 Oceanic Air Traffic Control Environment

Aircraft in the oceanic environment are largely out of radar coverage, therefore surveillance of the airspace occurs through position reports provided by the pilots approximately every 10 degrees of longitude or latitude, depending on speed and direction of flight. In New York oceanic sectors, flight strips, such as those seen in Figure 16, were used in December 2002 as the sole means of separation assurance. In Reykjavik Center, a situation display, as seen in Figure 17, is slowly being integrated into the separation assurance task. The situation display graphically depicts the information directly from the flight strips. Controllers are encouraged to use the Situation Display to assist in separation, however, Iceland's Operating Procedures still require that the controllers tactically ensure separation using the strips [13].

Figure 16: Oceanic controllers assure separation using flight strips without aid from a situation display in U.S. facilities. (Photo from Anchorage Oceanic Facility)
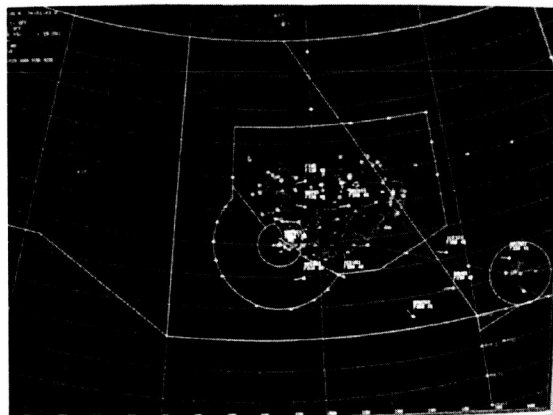

Figure 17: ATC Situation Display in Reykjavik Air Traffic Control Center.

Figure 18 depicts how air-ground communications are also complex due to the fact that the aircraft are out of VHF radio coverage and use HF to communicate through a third party operator. As a result, communication in the oceanic environment is cumbersome and slow which makes the control of traffic largely procedural. Standardizing phraseology structures the voice communications over oceanic airspace, and this maximizes the efficiency and minimizes errors as controllers communicate to pilots through a third party. The recent introduction of electronic messages mitigates some of the inefficiencies of communication in the oceanic environment. Reykjavik oceanic controllers communicate with the third party radio operator, intra-facility controllers, and some inter-facility controllers via electronic messages.

Because of the delayed surveillance and command paths, separation requirements between aircraft are large. Aircraft in the oceanic airspace are subject to separation minima of 50 to a 100 nm horizontally and longitudinally, and 1000-2000 ft vertically, depending on the airspace that the aircraft is flying through and its equipage. This significantly influences the traffic flow over the oceans and most importantly the number of aircraft that can be managed over the oceans at any given time.

Standard Routes

In the North Atlantic oceanic environment, the standard flows are designated tracks that are similar to ATC preferred routes in the domestic ATC environments. The tracks, depicted in Figure 19, are
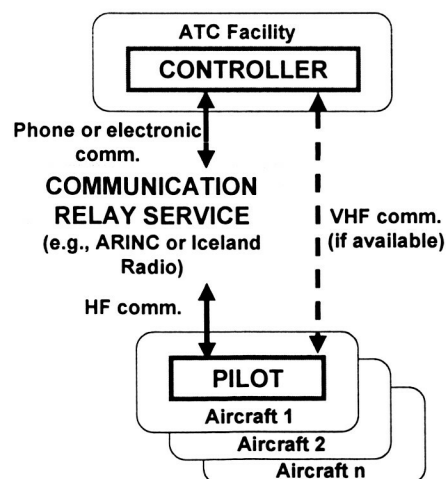

Figure 18: Controllers primarily communicate with pilots through a 3rd party operator over the oceans when VHF communication is not available
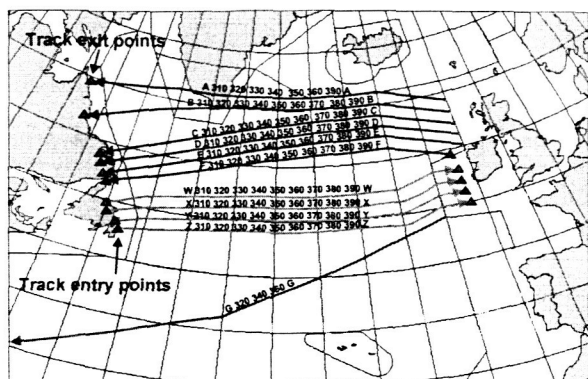
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Figure 19: Oceanic tracks structure over the North Atlantic. (Courtesy of Tom Reynolds)
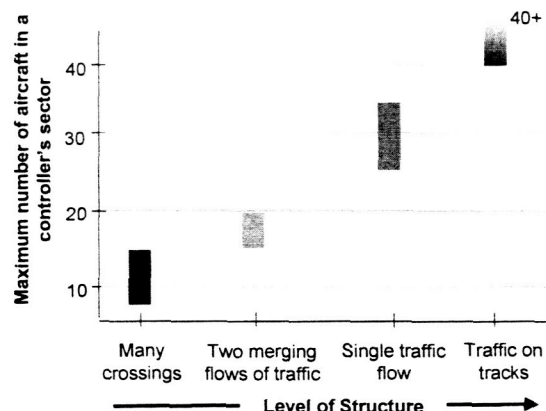

Figure 20: Maximum amount of traffic in a sector operating under different structural conditions as reported by Reykjavik oceanic controllers.
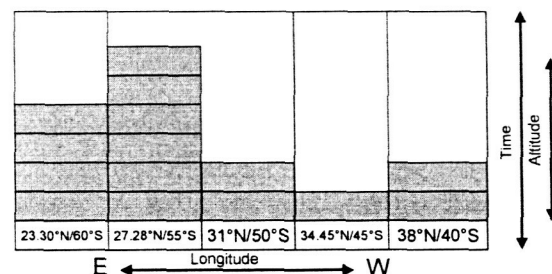

Figure 21: Example of flight strip arrangement in a New York Center oceanic sector mimicking the structure present in the actual environment.

different than ATC preferred routes in that the tracks are changed twice per day due to traffic predictions and weather forecast (primarily the location of the jet stream).

Conformance to the structure is vital for the air traffic controller to be able to control the airspace since it is the predominant source of information by which future position is projected. Controllers reported higher workloads in sectors where tracks are not used, and the aircraft are allowed to fly their own preferred routes. Figure 20 depicts a schematic summary of controllers' reported maximum traffic loads in sectors with different levels of lateral structure. As the level of lateral structure increases, so does the sector capacity. Without tracks, aircraft can no longer be controlled at the "flow level", reducing the number of aircraft that the controller can feasibly handle.

Cognitive complexity is increased further once merging or crossing traffic is introduced. In order to simplify the situation, the controllers move aircraft to a "safe" flight level when possible. If the airspace does not allow a dedicated flight level to crossing traffic, attention resources are required to monitor the aircraft's conformance and identify potential conflicts.

Groupings

It was observed that direction, time and altitude groupings were used in the Oceanic environment. These groupings were evident in the color and arrangement of the flight strips.

Oceanic controllers also mimic structure present in the airspace through the arrangement of flight strips. Figure 21 is an example of a flight strip bay arrangement used in a New York oceanic sector. The

columns are degrees of longitude, ordered from East to West. Within the columns, the flight strips are ordered by time. A single flight will have several flight strips, one in each of the columns, giving the controller not only the flight's current position, but also a physical representation of the projection of future positions. Through grouping aircraft in terms of time of arrival at the position reporting point, controllers can regulate the airspeed of the aircraft for longitudinal separation purposes. If aircraft are found to be arriving at a position report fix at the same time, the flight strips are then arranged by altitude.

In Reykjavik oceanic sectors, a similar flight strip bay arrangement is used on the electronic flight strip display in Figure 22. Contrary to New York oceanic sector procedures, Reykjavik controllers use 1 flight strip for each flight. Westbound flights are displayed in turquoise, while eastbound flights are displayed in yellow to clearly distinguish the direction of flight.
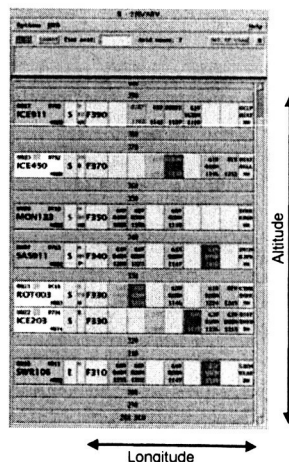
11

Figure 22: Example flight strip arrangement in Reykjavik with traffic flowing westbound (turquoise) and eastbound (yellow). Strips are arranged into altitude groupings with the strips aligning longitudinal progress.

The Reykjavik oceanic controller places the flight strip in an altitude grouping, then within this altitude arranges the strips by time. The structure of the lateral route of the flight on the flight strip then allows an easy comparison between flights for conflicting lateral waypoints. The highly structured environment using the oceanic tracks system encourages the controllers to use altitude as the primary means of separation assurance. Because of the reluctance to deviate from the highly proceduralized track structure and the monitoring demands required through speed separation, altitude separation emerges as the most robust and efficient means of separation while placing the lowest demand on the controllers' monitoring resources. This dominance of the altitude as the preferred means of oceanic separation simplifies the planning process as well.

Critical Points
The critical points in the oceanic environment are the position report points along the tracks and the entry fixes onto the tracks. Figure 23 contains last reported positions of the aircraft under oceanic control in the North Atlantic. The oceanic controller, using the flight strip arrangement discussed above, then determines whether any of the aircraft will be in conflict given the information provided and projected at these position report points.

The entry points of the tracks are particularly important points for scheduling the appropriate procedural separation between aircraft entering the tracks. Because such increased separation is required
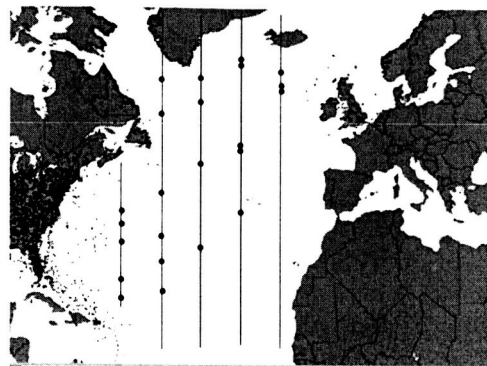

Figure 23: Position report points: the "critical points" in the oceanic environment. (Data from Flight Explorer, January, 2003)

longitudinally between aircraft on the tracks, much of the separation task is performed in the area immediately before the track entry points so that sufficient procedural separation exists at the point of entry.

The cognitive projection task in the oceanic environment appears to be primarily time-based projection, in addition to the limited use of the spatial-based projection task used in the TRACON and En Route environments. Time-based projection is used because of the procedural separation requirements [14] as well as the operating procedures that do not allow controllers to rely on position information from the situation display provided [13]. It is hypothesized that time-based projection is innately different than spatial-based projection, requiring different information and training to perform it to the standards necessary in ATC.

Currently there are many initiatives ongoing for improving communication and surveillance in the oceanic environment to enhance safety and increase traffic [13]. Technologies are being developed incorporating a highly reliable and accurate graphical overview of the airspace. With the new technologies, the oceanic controllers will be able to rely solely on the graphical overview. A question that designers need to address is how will changing the task from a procedural separation task to a radar separation task affect the controller's ability to provide separation assurance over the ocean, and what, if any, information and training is required to address these issues.

5 Conclusions

The TRACON, En Route, and Oceanic ATC operational environments appear to be very different, but the analyses provided in this paper support the

hypothesis that structure-based abstractions are used as a complexity-reduction mechanism in each context. Procedures and airspace within each environment support the tasks that can become complex given high amounts of traffic and limiting constraints in the environment. Key structure-based abstractions were discovered across domains, but the details in how these abstractions were implemented differ.

Standard flows are evident as a means of aiding in the projection tasks in normal circumstances and as a template for alternate routings in cases of severe weather or traffic. The TRACON's standard flows emerge from SOP-based standard arrival routes and standard departure routes. The En Route environment standard flows are determined by the ATC preferred routings, STARs and SIDs. The oceanic track system provides the standard flows across the Northern Atlantic Ocean.

Groupings are used to simplify the cognitive processes, particularly projection, planning, and implementing. Altitude and airspeed groupings are used in the TRACON to reduce the dimensionality of the complex 4-D spatial projection task required. Altitude groupings are used in the En Route environment. In oceanic operations, the task-relevant groupings are time to the next position-report point and altitude.

Critical points were observed in the three environments, and these points allowed the projection task to become a phasing task to merge or handoff points in the ATC sectors. In both the TRACONs and the En Route Centers, important critical points include merge points, handoff points, and points where aircraft were put into holding patterns. Oceanic environment revealed critical points as position report points, the only points at which surveillance could be conducted.

Structure-based abstractions appeared to particularly support the Situation Awareness Level 3 projection task from Figure 1. How the support was provided depended on the operational context and constraints of the environment.

In the TRACON, most of the separation requirements are in spatial terms (miles) while some of the separation requirements are in terms of time (minutes). The radar screen supports a spatial form of projection, monitoring, and evaluating. Controllers were found to apply a simple cognitive heuristic to change the minutes-in-trail restrictions to miles-in-trail.

The En Route Center separation requirements contain equally spatial (miles-in-trail) constraints and time (metering, minutes-in-trail) constraints. However, the radar displays, similar to the TRACON support spatial projection, monitoring, and evaluating.

Because of the lack of adequate surveillance technologies in the Oceanic environment, spatial displays are not currently used for separation purposes. The primary means of assuring separation are the flight strips, and they support a procedural, or time-based, form of separation assurance. The separation requirements in the Oceanic environment are mostly time-based, but include spatial-based requirements as well. Proposed future oceanic technologies include spatial displays, and these tools encourage a progression to primarily spatial-based separation requirements.

In this paper, the details of structure-based abstractions were found to be highly dependent on the context in which they are applied. The projection task and how the abstractions were applied depended both on whether the support tools and separation requirements were in terms of space or time. Thus, designers of decision support tools should consider both the effect of structure-based abstractions and the type of projection, time-based or spatial-based, that the controller is required to do and provide support to this cognitively difficult task.

Acknowledgements

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